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On the farsightedly and myopically stable international environmental agreements

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Abstract

We investigate the stability of International Environmental Agreements. The analysis of Chwe is extended by investigating the question how to find farsightedly stable coalitions. The myopic stability concept of d'Aspremont, Jacquemin, Gabszeweiz, and Weymark and the farsighted stability concept of Chwe are compared. Farsighted stability, direct and indirect domination are discussed. Considering of the direct domination, we check for the single-step stability by comparing the profits of every coalition member after one-step deviation has occurred, while considering the indirect domination (farsightedness) we check for the multistep stability by comparing the profits of every coalition member after a series of deviations have come to an end. On the contrary, myopic stability assumes that players look only one step ahead. The improvement of farsightedly and myopically stable coalitions to the environment quality and welfare are compared. Only the farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ improves the welfare and abatement by 20% and 79% in comparison to all three myopically stable coalitions together. Algorithms are developed, which can find all farsightedly stable coalitions structures.

Considerations for Management

Taking into account findings, management considerations may include:

- Myopically stable coalitions are typically subsets of farsightedly stable coalitions.

- Farsightedly stable coalitions are the largest stable coalitions without side payments, and bring the biggest improvement in environmental quality and welfare.
- We predict the formation of coalitions that are bigger than myopically stable but smaller than farsightedly stable coalitions. This conclusion is valid under the assumption that transfers are not allowed.

KEYWORDS

coalition formation, farsighted stability, game theory, integrated assessment modeling, myopic stability

1 | INTRODUCTION

The literature on International Environmental Agreements (IEA) has two conflicting views. One is based on cooperative game theory and concludes that the grand coalition is stable by using the core concept, assuming linear utility, and implementing transfers, as countries have different benefits and cost functions from greenhouse gas emission abatement (Chander, 2007; Chander & Tulkens, 1997; Eyckmans & Tulkens, 2003). The other view is rooted in the noncooperative game theory, which became the dominant path in the literature (Barrett, 1994, 2003; Botteon & Carraro, 2001; Finus, van Ierland, & Dellink, 2006; McGinty, 2007; Osmani & Tol, 2010; Rubio & Ulph, 2006).

The usual approach of noncooperative game theory to stable IEAs is based on the idea developed for cartel stability (d'Aspremont, Jacquemin, Gabszeweiz, & Weymark, 1983) and requires so-called internal and external stability. Internal stability means that no country has an incentive to leave a coalition, while external stability means that no country has an incentive to join a coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically small.

This paper focuses on a comparison between myopic and farsighted stability.

Farsighted stability developed further the notation of stable sets of von Neumann and Morgenstern (1947). Stable sets are defined to be self-consistent. The notion is characterized by internal and external stability. Internal stability guarantees that the solution set is free from inner contradictions, that is, any two outcomes in the solution set cannot dominate each other, and external stability guarantees that every outcome excluded from the solution set is accounted for, that is, it is dominated by some outcome inside the solution. Harsanyi (1974) criticizes the von Neumann and Morgenstern solution also for its failing to incorporate foresight. He introduced the concept of indirect dominance to capture foresight. One outcome indirectly dominates another, if there exists a sequence of outcomes starting from the dominated outcome and leading to the dominating one, and at each stage of the sequence the group of players required to enact the inducement prefers the final outcome to its status quo. His criticism inspired a series of works on abstract environments including among others those of Chwe (1994), Mariotti (1997), and Xue (1998). Chwe (1994) introduces the notion of farsighted stability, which is applied to the problem of IEAs by Diamantoudi and Sartzetakis (2002), Eyckmans (2003), and Osmani and Tol (2009). Diamantoudi and Sartzetakis (2002) consider identical countries, while asymmetric countries are taken into account in our model. Eyckmans (2003) studies only single farsightedly stable coalitions, while we allow multiple farsightedly stable coalitions. Similar to Osmani and Tol (2009), a more systematic way of finding farsightedly stable coalitions is introduced. But different to Osmani and Tol (2009), a more general approach is used, and the focus is on the comparison between myopic and farsighted stability.

The welfare functions of 16 world regions are taken from the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model Version 2.8 (Tol, 1999a,b, 2001, 2002c). The social welfare functions are per-member partition functions in our game-theoretical framework.

The paper extends the analysis of Chwe (1994), on the issue of how to find farsightedly stable coalitions, and concentrates on comparison between farsighted and myopic stability.

Furthermore, in the spirit of the Consistent Set of Chwe (1994), we define Dynamic Farsighted Coalition Structure Set (DFCS); if a coalition structure does not belong to DFCS, then it is indirectly dominated by another coalition structure which belongs to DFCS. Being aware of cycles, we follow Chwe and build a weak solution, in the sense that outcome belonging to DFCS are only possibly stable.

We refine further the farsighted stability concept to the preferred farsighted stability. The preferred farsightedly stable coalition is a farsightedly stable coalition where the majority of country members reach higher profits in comparison to any other farsightedly stable coalition.[1] The main contribution of the paper is a detailed discussion and comparison of myopic stability and farsighted stability.

We show that the myopically stable coalitions are often subcoalitions of farsightedly stable coalitions. Besides, farsightedly stable coalitions can be frequently the largest size stable coalition that game theory, without side payments, can realize. We would like to clarify that these conclusions are valid under *the assumption that transfers are not considered*. If one allows transfers like in papers of Weikard and Dellink (2014) and Osmani (2015) the size of myopically stable coalitions can be large too; in paper of Osmani (2015) a myopically stable coalition can include even 15 regions, when the grand coalition has only 16 regions, while in the paper by Weikard and Dellink (2014) even the grand coalition can be myopically stable.

Moreover, the farsightedly stable coalitions always create the biggest improvement in environmental quality and welfare.

Similarly to preferred farsightedly stable coalitions, we introduce preferred myopically stable coalitions. All myopically stable coalitions are found, and multiple myopic coalitions are compared with multiple farsighted ones.

The paper is organized as follows.[2] In Section 2, the game-theoretic model for farsighted stability, and direct and indirect domination are presented; a numerical example is also presented in order to illustrate our concepts on farsighted stability. Section 3 introduces the DFCS, and discusses how to find single and multiple farsightedly stable coalitions. In Section 4, cost-benefit functions from the FUND model are introduced, and single farsightedly stable coalitions are found. In Section 5, the game-theoretic model for myopic stability is presented, and the single myopically stable coalitions are found. Section 6 discusses the preferred stable (farsighted or myopic) coalitions, and finds multiple preferred stable coalitions. Section 7 introduces a detailed discussion on the comparison between myopic and farsightedly stable coalitions. Section 8 provides the conclusions. Appendix A briefly introduces the FUND model. In Appendix B, the algorithm on how to find multiple farsightedly stable coalitions, is presented.[3]

2 | THE GAME-THEORETICAL MODEL FOR FARSIGHTED STABILITY

Similarly to Chwe (1994), a game Γ is defined as, $\Gamma = (N, O, \{\prec_i\}_{i \in N}, \{\to_C\}_{C \subset N, C \neq \emptyset})$ where N is the set of players, O is the set of all coalition structures (which are also outcomes), $N \neq \emptyset, O \neq \emptyset$; $\{\prec_i$

$\}_{i \in N}$ are the strong preference relation of the players defined on O; the preference relation is *reflexive, complete, and transitive*. Before explaining the game further, let us define the coalition structure:

Definition 2.1. A coalition structure $a = \{C_1, C_2, \ldots, C_m\}$ is a partition of the set of players $N = \{1, 2, \ldots, n\} : C_i \cap C_j \neq \emptyset$ where $\bigcup_{i=1:m} C_i = N$.

A coalition structure fully describes how many coalitions are formed, how many members they have, and also how many single players there are. The relation $\rightarrow_{C_1}$ introduces the actions that are available to coalition C_1; $a_1 \rightarrow_{C_1} a_2$ indicates that if coalition structure a_1 is the status quo, coalition C_1 can make a_2 the new status quo.

The game is “played” in the following way: when the game starts, there is a coalition structure (or outcomes) status quo called a_1. If the member of coalition C decides to change the status quo from a_1 to a_2, or $a_1 \rightarrow_C a_2$, then the new status quo becomes a_2. This change of a status quo is called a coalition's move or deviation, from a_1 to a_2. From this new status quo a_2, another coalition might move, and so on. If a status quo a_3 is reached, and no player prefers to move, then a_3 is called stable and the game is over. The game does tell you if a move or deviation is possible, thus if a coalition structure a_m is possible or not.

The game is of a cooperative and noncooperative spirit. The selfishness of players shapes the aspects of *the noncooperative approach*. The idea of farsightedness means that one should check for multistep stability by comparing the preference of a coalition member after a series of deviations has come to an end. The deviation is possible only if players display *a cooperative attitude* by forming a coalition which they prefer.

As the game is defined, we will go on discussing direct and indirect domination.

If $a_1 \prec_i a_2$, $\forall i \in C$, we write $a_1 \prec_C a_2$.

Definition 2.2. A coalition structure a_1 is directly dominated by the coalition structure a_2, or $a_1 < a_2$, if there exists a C_1 such that $a_1 \rightarrow_{C_1} a_2$ and $a_1 \prec_C a_2$.

The definition of indirect dominance taken from Harsanyi (1974) is introduced below:

Definition 2.3. A coalition structure a_1 is indirectly dominated by the coalition structure a_m, or $a_1 \ll a_m$, if there exists $a_1, a_2, a_3, \ldots, a_m$ and $C_1, C_2, C_3, \ldots, C_{m-1}$ such that $a_i \rightarrow_{C_i} a_{i+1}$, and $a_i \prec_{C_i} a_m$, where $i = 1, 2, 3, \ldots, m-1$.

Henceforth, we will only focus on the “effective relation” that leads to indirect domination. This fits in the spirit of farsighted stability as the farsighted players can see all possible deviations ahead, and they are going to deviate only if they see further deviations ahead, which leads to an indirect dominance. Note that if $a_1 < a_2$, then $a_1 \ll a_2$.

Definition 2.4. A coalition structure a_1 is a candidate for being farsighted stable only if it is not indirectly dominated.

Here we stick with a weak solution like the original farsighted coalitional stability of Chwe (1994). We simply consider any coalition, which is not indirectly dominated, as a candidate for being farsightedly stable.

At this point, the definition of cycles has to be given:

Definition 2.5. A cycle is a chain of coalition structures $a_1 \rightarrow_{C_1} a_2 \rightarrow_{C_2} a_3 \;\ldots\; a_{n-1} \rightarrow_{C_{n-1}} a_n \rightarrow_{C_n} a_1$, where at least three coalition structures $a_i \in \{a_1, \ldots a_n\}$ cannot be indirectly dominated.

In testing for farsightedly stable coalitions, cycles can be formed, and every coalition structure, which is a part of a cycle, none which are indirectly dominated can be found.

In order to compute candidates for the farsightedly stable coalitions, we assume (at this point) that *only one coalition is formed*. There are three ways that a coalition can change when one coalition is formed; a coalition gets smaller, gets bigger, or some members leave a coalition and some others join it. When a coalition gets smaller then the internal indirect domination takes place; when a coalition gets bigger then the external domination takes place; when some members leave a coalition, while some other joins it then the subcoalition domination takes place. In order to find the farsightedly stable coalitions, *all types of indirect domination (internal, external, and subcoalition) are considered as a combinatorial process*. The definition of internal indirect domination is introduced below.

Definition 2.6. a_1 is internally indirectly dominated by a_m, or $a_1 \ll a_m$, if there exists $a_1, a_2, a_3, \ldots, a_m$ and $C_1, C_2, C_3, \ldots, C_{m-1}$ where $C_1 \supset C_2 \supset C_3, \ldots, C_{m-2} \supset C_{m-1}$ and $a_i \rightarrow_{C_i} a_{i+1}$, and $a_j \prec_{C_j} a_m$ where $i, j = 1, 2, 3, \ldots, m-1$.

If a coalition shrinks and its remaining members prefer the final coalition compared to the initial one, *an internal indirect domination* becomes possible.

Definition 2.7. a_1 is externally indirectly dominated by a_m, or $a_1 \ll a_m$, if there exists $a_1, a_2, a_3, \ldots, a_m$ and $C_1, C_2, C_3, \ldots, C_{m-1}$ where $C_1 \subset C_2 \subset C_3, \ldots, C_{m-2} \subset C_{m-1}$ and $a_i \rightarrow_{C_i} a_{i+1}$, and $a_j \prec_{C_j} a_m$ where $i, j = 1, 2, 3, \ldots, m-1$.

If a coalition grows, and its remaining members prefer the final coalition compared to the initial one, *an external indirect domination* becomes possible.

Definition 2.8. a_1 is a subcoalitionally indirectly dominated by a_m, or $a_1 \ll a_m$, if there exists $a_1, a_2, a_3, \ldots, a_m$ and $C_1, C_2, C_3, \ldots, C_{m-1}$ where $C_l \cap C_{l+1} \neq \emptyset$ where $l = 1, 2, 3, \ldots, m-1$ and $a_i \rightarrow_{C_i} a_{i+1}$, and $a_j \prec_{C_j} a_m$ where $i, j = 1, 2, 3, \ldots, m-1$.

The indirect subcoalition domination occurs when a number of old coalition members leave and a number of new members join the initial coalition. The new coalition may be larger or smaller than the original one. However, if a part of the old coalition members (a subcoalition), and the new coalition members form a coalition, and prefer it compared to the initial coalition, *a subcoalition indirect domination* becomes possible.[4]

Definition 2.9. If a coalition structure a_1 is not externally $\wedge$ internally $\wedge$ subcoalitionally indirectly dominated then coalition structure a_1 is farsightedly stable or a part of cycle.

If we can transform the preference relations to a payoffs comparison, then it can be easily checked *by a combinatorial algorithm* if a coalition is internally, externally, or subcoalitionally indirectly dominated. In order to be able to compare the payoff of the coalition members, we need to introduce the definition of partition function. Let us recall that $N = \{1, ..., n\}$ is the set of players, and that nonempty subsets of N are called coalitions. A partition (or coalition structure) a is a set of disjoint coalitions, $a = \{P_1, P_2, ..., P_k\}$, so that their union is N; the set of all partitions is $\mathcal{P}$, and the set of partitions of a coalition C of N (that is, all the partitions where coalition C is part of them) is $\mathcal{P}(C)$.

Definition 2.10. The partition function is a mapping $V(C, \mathcal{P}) : (C, \mathcal{P}) \mapsto \mathfrak{R}$ where $C \in \mathcal{P}$, which assigns a value to each coalition in every partition.

Definition 2.11. The per-member partition function is a mapping $v(i)_{i \in C}(C, \mathcal{P}) : (C, \mathcal{P}) \mapsto \mathfrak{R}$ where $C \in \mathcal{P}$, which assigns a payoff value $v(i)^*_{i \in C}(C, \mathcal{P})$ to every member of each coalition in every partition.

The per-member partition function $v(i)_{i \in C}(C, \mathcal{P})$ gives a payoff value $v(i)^*_{i \in C}(C, \mathcal{P})$ (from now on, I will write simply $v(i)^*_{i \in C}$ for every coalition member). This helps us to transform the preference relation to a comparison of coalition member payoffs.

TABLE 1 Our data for the year 2005

	α	β	E	Y
USA	0.01515466	2.19648488	1.647	10,399
CAN	0.01516751	0.09315600	0.124	807
WEU	0.01568000	3.15719404	0.762	12,575
JPK	0.01562780	−1.42089104	0.525	8528
ANZ	0.01510650	−0.05143806	0.079	446
EEU	0.01465218	0.10131831	0.177	407
FSU	0.01381774	1.27242378	0.811	629
MDE	0.01434659	0.04737632	0.424	614
CAM	0.01486421	0.06652486	0.115	388
LAM	0.01513700	0.26839935	0.223	1351
SAS	0.01436564	0.35566631	0.559	831
SEA	0.01484894	0.73159104	0.334	1094
CHI	0.01444354	4.35686225	1.431	2376
NAF	0.01459959	0.96627119	0.101	213
SSA	0.01459184	1.07375825	0.145	302
SIS	0.01434621	0.05549814	0.038	55

Notes: In the table, α is the abatement cost parameter (unitless), β is the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon), E is the carbon dioxide emissions (in billion metric tonnes of carbon), and Y is the gross domestic product (in billions US dollars). *Source:* FUND Version 2.8, Year 2005 (see http://www.fund-model.org for a detailed description of FUND and links to published papers)

Definition 2.12. A coalition C prefers coalition structure a_j in comparison to a_m (or $a_j \prec_C a_m$) if and only if:

- $v(i)_{i \in C}^{a_j *} > v(i)_{i \in C}^{a_m *} \ \ \forall i \in C$
- $v(i)_{i \in C}^{a_j *}$, $v(i)_{i \in C}^{a_m *}$ are the per-member partition function values of a member i of coalition C with coalition structures a_j and a_m, respectively.

By comparing the payoffs of coalition members between different coalition structures, it can be easily checked *with a combinatorial algorithm* if a coalition is internally, externally, or subcoalitionally indirectly dominated.

2.1 | Example

The full example of computation of single farsightedly stable climate coalitions is presented in Osmani and Tol (2009), but here we present a small part of the numerical computations which test and find the three-member coalitions that are not farsightedly stable, and *illustrate numerically the concept of internal, external, and subcoalition stability* presented in Section 2. We use the per-member partition function taken from the FUND model developed by Richard Tol (Tol, 1999a,b, 2001, 2002c). See Section 4 for a detailed description of *per -member partition function*. Table 1 shows the parameters of per-member partition function estimated by the FUND model, and 16 regions-countries (United States of America USA, Canada CAN, Western Europe WEU, Japan and South Korea JPK, Australia and New Zealand ANZ, Central and Eastern Europe EEU, the former Soviet Union FSU, the Middle East MDE, Central America CAM, South America LAM, South Asia SAS, Southeast Asia SEA, China

TABLE 2 Three-member coalitions which are not externally farsightedly stable

Coalition	Pr_3	Pr_5	*Coalition*	Pr_3	Pr_5
USA	0.5336	0.5336	**USA**	0.5765	0.6916
LAM	0.0614	0.0614	**SEA**	0.177	0.2057
CHI	0.7613	0.7613	**CHI**	0.8048	0.817
NAF	0.322	0.322	NAF	0.3533	0.3976
SSA	0.3573	0.3573	SSA	0.3921	0.4173

TABLE 3 Three-member coalitions which are not externally farsightedly stable

Coalition	Pr_3	Pr_5	*Coalition*	Pr_3	Pr_5
USA	0.457	0.6916	**CAN**	0.0198	0.0204
SEA	0.177	0.2057	EEU	0.0216	0.0217
CHI	0.7766	0.817	**CAM**	0.0142	0.0144
NAF	0.2203	0.3976	SAS	0.075	0.0753
SSA	0.2398	0.4173	**SIS**	0.0118	0.012

TABLE 4 Three-member coalition which is not externally farsightedly stable

Coalition	Pr_3	Pr_5
CAN	0.0199	0.0204
EEU	0.0216	0.0217
CAM	0.0142	0.0144
SAS	0.0751	0.0753
SIS	0.0118	0.012

CHI, North Africa NAF, Sub-Saharan Africa SSA, and Small Island States SIS) that FUND takes into account *for the single year horizon 2005, which this example considers*. The FUND model is briefly described in Appendix A. The members of coalition behave cooperatively with each other and maximize their joint welfare, and take the welfare of single countries as given; every single country behaves noncooperatively by maximizing its own welfare and taking the welfare of coalition members and the rest of single countries as given.

First, we note that all profitable climate coalitions are internally farsightedly stable (including the three-member coalitions). Three-member coalitions which are not externally farsightedly stable are presented in Tables 2, 3, and 4.

The first column of Table 2 presents the members of five-member final coalitions. The three countries of the coalition that are inspected are labeled in bold letters, while the members that join the initial coalition are labeled in normal typeface. The second column of Table 2, Pr_3, displays the profits (in billions of dollars) of the final coalition members when only the three-member coalition exists, while the third column Pr_5 shows the profits of final coalition members when only the five-member coalition exists. The profits of each country are higher when the five-member coalition is formed (Pr_5) in comparison to the profits when the three-member coalition is formed (Pr_3). As a result, the three-member coalition (*USA, LAM, CHI*) is not externally farsightedly stable. Columns four, five, and six of Table 2 are similar to columns one, two, and three, and Tables 3 and 4 are similar to Table 2.

Tables 5 and 6 introduce the three-member coalitions which are not sub-coalition farsightedly stable. In the first column, the country members which change their position (join or leave the initial coalition) are placed. The three countries of a primary coalition which is inspected are labeled in bold letters,

TABLE 5 Three-member coalition which is not subcoalition farsightedly stable

Coalition	Pr_{3old}	Pr_{3new}
USA^*	0.4476	0.457
JPK	−0.3032	−0.3467
NAF*	0.2057	0.2203
SSA*	0.2285	0.2398

TABLE 6 Three-member coalition which is not subcoalition farsightedly stable

Coalition	Pr_{3old}	Pr_{3new}
USA^*	0.4824	0.5336
CAN	0.0205	0.0311
FSU	0.241	0.3945
LAM*	0.0599	0.0614
CHI^*	0.7149	0.7613

while the three members of the final coalition are marked with an asterisk on the top-right. It is clear that countries in bold letters who have an asterisk on the top-right are simultaneous members of a primary and final coalition. The second column of Table 2, Pr_{3old}, presents the profits of final coalition members when only the primary three-member coalition is formed, while the third column of Table 2, Pr_{3new}, introduces the profits when the final three-member coalition is built. The profits of members of final three-member coalitions (*with an asterisk on the top-right*) are greater when the final three-member coalition is formed Pr_{3new} compared to the primary three-member coalition Pr_{3old}. It follows that the three-member coalition (*JPK, NAF, SSA*) is not subcoalition farsightedly stable. Finally, Table 6 is similar to Table 5.

3 | COMPUTATIONAL ASPECTS OF FINDING SINGLE FARSIGHTED STABLE COALITION

In this section, we clarify the proceeding of computing a *single* farsighted stable coalition.

Let us first define the full-noncooperative behavior, which is necessary to define the profitable coalition, crucial for calculation of farsightedly stable coalitions.

Definition 3.1. The situation in which each country maximizes its own profit, and the maximum coalition size is unity, is referred to as the full-noncooperative structure (or a_{FNS}).

This is a standard Nash equilibrium. A coalition that performs better than the full-noncooperative structure is *a profitable coalition*. Only profitable coalitions are tested, which is sufficient to find all the single farsightedly stable coalitions (see Observation 3.3). The definition of a profitable coalition is introduced below:

Definition 3.2. A coalition C in coalition structure a_c is profitable (or individual rational) if and only if it satisfies the following condition:

- $v(i)_{i\in C}^{a_c*} > v(i)_{i\in C}^{a_{FNS}*}$
- $v(i)_{i\in C}^{a_c*}$, $v(i)_{i\in C}^{a_{FNS}*}$ are per-member partition function values of a player i of coalition C with coalition structure a_c and a_{FNS}, respectively.

Considering only profitable coalitions also reduces the computational effort required to find farsightedly stable coalitions. The profitability condition demands more than the superadditive property, which requires that two different coalitions should generate more profits (or welfare) by joining forces than by remaining separate; see Definition 4.1.

Observation 3.1. If there are no profitable coalitions, then the only farsightedly stable coalitions are the coalitions with a unity size formed in the full-noncooperative structure.

Proof. That there are no profitable coalitions means that there is no direct or indirect domination process that originates from the full-noncooperative structure (Nash equilibrium). This completes the proof. ■

We present below an existence proof for farsightedly stable coalition:

Observation 3.2. There always exists a candidate for a farsightedly stable profitable coalition.

Proof. Let take a random profitable coalition C_1. There are two possibilities:

(i) If the coalition C_1 is *not* indirectly dominated, then C_1 is a candidate for being farsightedly stable. A candidate for being farsightedly stable means the coalition C_1 is farsightedly stable or belongs to a cycle.

(ii) If the coalition C_1 is indirectly dominated, then there is a coalitions chain $C_1, C_2, \ldots, C_m$ where C_m indirectly dominates C_1. If C_m is *not* indirectly dominated, then C_m is a candidate for being farsightedly stable; if C_m is indirectly dominated, then there exists a coalitions chain where the last coalition (in the coalitions chain) dominates C_m. As coalitions chains that leads to indirect dominations are finite, they will end to a certain coalition C_l, which is going to be a candidate for being farsightedly stable. This completes the proof. ■

The Observations 3.1 and 3.2 provide a proof of existence of farsightedly stable coalitions; Observations also leave no doubt that there is a close connection between a profitability condition and farsighted stability.[5] As at the moment only single coalitions are being tested, instead of talking about coalition structure, we are only discussing coalitions. Finding profitable farsightedly stable coalitions is computationally challenging, but a straightforward job. One finds all profitable coalitions and begins to test one by one if they are externally, internally, or subcoalitionally indirectly dominated by other coalitions. The profitable coalitions, which are not indirectly dominated, are farsightedly stable or belong to a cycle. But can we find the nonprofitable farsightedly stable coalitions, if there are any? It is crucial to note that, in real-world problems with asymmetric countries, one expects to have far more nonprofitable coalitions than profitable ones (because of asymmetry). This implies that the question has an important computational aspect.

In order to answer these questions, we need first to define *the positive, negative, and neutral spillover property*.

Definition 3.3. If a game for any two coalitions $C_1 \subset N$ and $C_2 \subset N$ such that $C_1 \neq C_2$ satisfy:

- $\forall\, k \notin C_1 \cup C_2 \quad v(k)^{C_1 \cup C_2} > v(k)^{C_1} \wedge v(k)^{C_1 \cup C_2} > v(k)^{C_2}$, *we say the game exhibits positive spillover property*
- $\forall\, k \notin C_1 \cup C_2 \quad v(k)^{C_1 \cup C_2} < v(k)^{C_1} \wedge v(k)^{C_1 \cup C_2} < v(k)^{C_2}$, *we say the game exhibits negative spillover property*
- $\forall\, k \notin C_1 \cup C_2 \quad v(k)^{C_1 \cup C_2} = v(k)^{C_1} \wedge v(k)^{C_1 \cup C_2} = v(k)^{C_2}$, *we say the game exhibits neutral spillover property*.

Clearly if the positive spillover property is not satisfied, then it does not mean the negative spillover property is satisfied. Usually one can assume that some players satisfy the positive spillover property, while some others the negative or neutral spillover property.

It is reasonable to take the full-noncooperative structure as *a starting point*; we find all profitable coalitions, and test every *profitable coalition* whether it is farsightedly stable.

Our combinatorial proceeding realizes that all possible coalitions, which can dominate our initial coalition (let say C_l), are considered. Clearly all possible coalitions, which can dominate our coalition C_l, can be divided into three categories (C_1, C_2, C_3):

- $C_1 \subset C_l$, which are checked when internal indirect domination is examined
- $C_2 \supset C_l$, which are tested when external indirect domination is investigated
- $C_3 \cap C_l \neq \emptyset$, which are inspected when sub-coalition indirect domination is considered.

As a consequence, we ascertain whether there exists a coalition which dominates our coalition C_n[6]. It is clear that this is a huge combinatorial effort.[7]

Now we are able to state a very useful observation which makes sure that we are able to find all farsightedly stable coalitions (profitable or nonprofitable), even if we use as a starting point only profitable coalitions. This is especially important from a computational point of view, as in games with asymmetric players, there are far more nonprofitable coalitions than profitable ones.

Observation 3.3. A nonprofitable coalition C_m is farsighted stable if and only if:

(i) the positive spillover or neutral spillover property is not satisfied

(ii) $\exists\ C_1 \subset C_m$, and C_1 is profitable; $\exists\ C_2 \mid C_2 \cap C_m \neq \emptyset$ where C_2 is profitable, and C_2 is directly or indirectly dominated by C_m, and C_m is not directly or indirectly dominated by any coalition.

Proof. Proof, First Statement:

First direction:

If a nonprofitable coalition C_m is farsightedly stable, then the positive and neutral spillover property is not satisfied.

Suppose that there is a nonprofitable farsightedly stable coalition C_n, and the positive spillover property is satisfied. As C_n is not-profitable, then:

$$\exists\ a\ player\ l \in C_n | v(l)^{C_n *} < v(l)^{a_{FNS} *}. \tag{1}$$

Suppose that the player l leaves the coalition C_n and becomes a single player, then as the positive spillover property is satisfied we have:

$$v(l)^{C_n} > v(l)^{a_{FNS}}. \tag{2}$$

Equation (2) contradicts equation (1), which proves (by contradiction) that if we have a farsightedly stable nonprofitable coalition, then the positive spillover property is not satisfied.

Proof Second direction: The proof for the second direction (and neutral spillover property) is similar to the above one, so we omit it.

Proof Second Statement:

First direction: *If a nonprofitable coalition C_m is farsightedly stable*, then there is a profitable subcoalition $C_1 \subset C_m$. Besides, there is C_2 such as $C_2 \cap C \neq \emptyset$, C_2, which is directly or indirectly dominated by C_m, and moreover C_m is not directly or indirectly dominated by any coalition.

Part 1, First direction: Suppose that every subcoalition of any nonprofitable farsightedly stable (FS) coalition C_m has a country that receives a lower payoff than in the full-noncooperative behavior, then the coalition C_m is not FS. The coalition is not FS because it is possible to build an effective relation to dissolve the coalition:

$$C_m \to C_{m-1}, \dots, C_1 \to a_{FNS} \ as \ \forall C_l 1 \le l \le m \exists \ i \in C_l \ where \ v(i)^{C_l} > v(i)^{a_{FNS}}. \tag{3}$$

The dissolving process is simple. Every country with a lower profit than in the full-noncooperative structure leaves the coalition. As every subcoalition has one such country, the coalition is not FS. As a consequence, coalition C_1 must have a profitable subcoalition in order to have a chance of being FS, which completes the first part of the proof.

Part 1, Second Direction: The proof of the second direction is similar to the first direction, so we omit it.

Proof Part 2: Let us suppose that we have the chain of the effective relations, where C_m is a nonprofitable farsightedly stable coalition:

$$a_{FNS} \to C_1, \dots, C_{m-1} \to C_m. \tag{4}$$

We only focus on an "effective relation" that leads to indirect domination; as a consequence a nonprofitable coalition does not indirectly dominate the full noncooperative structure. This implies that in the chain on the effective relation (4) $\exists \ C_i$ which is profitable $i \in N, 1 \le i \le m$. ■

Corollary 3.1. *If the positive or neutral spillover property is satisfied for all players, then all farsightedly stable coalitions are profitable.*

Proof. This follows immediately from Observation 3.3. ■

We should now mention an important assumption of our theoretical framework:

Assumption 1. A farsighted player does not free-ride as he knows that if he free-rides, the other players are going to follow him, and all the players will therefore decrease their payoffs. As it is expected, a farsighted player displays a type of "farsighted individual rationality."

The free-riding of any player $i \in C$ is deterred based on the threat of the rest of the players of coalition C, who will free-ride if any player i free-rides. The way that free-ride is deterred is not unusual in game-theoretical modeling of coalition for environmental protection; it is very similar to seminal paper of Chander and Tulkens (1995).

The experimental game theory supports this mode of behavior too; please see Fehr and Gaechter (2000) and Ostrom (2000). It also fits well with the farsighted behavior, as it takes into account the counter reaction of other players by showing, as it is expected, *a type of "farsighted individual rationality."* One point has to be made here; a specific country can still leave the coalition in a public good game, not only because of free-riding, but for example, in a nonprofitable coalition, when a country can leave the coalition if its welfare is lower than in a fully noncooperative structure.

3.1 | DDSCS and DFCS

We characterize the set of all Direct Dominating Stable Coalitions Set (DDSCS) as $Coal_{dd}$.

Definition 3.4. A set Q is a DDSCS if and only if:

- a coalition structure $\mathbf{a} \in Q$ then $\mathbf{a}$ is not directly dominated

- $\forall$ *coalition structure* $\mathbf{b} \notin \mathcal{Q} \, \exists$ *a coalition structure* $\mathbf{c} \in \mathcal{S} \mid \mathbf{b} < \mathbf{c}$.

The definition first indicates that any coalition structure a that belongs to DDSCS is not directly dominated. Second, if a coalition structure **b** does not belong to DDSCS, there exists another coalition structure $c \in DLCS$, which dominates **b** directly.

In the spirit of Chwe (1994), we characterize the set of all farsightedly stable coalitions $Coal_{fs}$ as the DFCS (or one can call it the Indirect Dominating Coalition Structure Set).

Definition 3.5. A set $\mathcal{S}$ is the DFCS if and only if:

- $\forall$ coalition structure $\mathbf{a} \in \mathcal{S}$ **a** is farsightedly stable or belongs to a cycle
- $\forall$ *coalition structure* $\mathbf{b} \notin \mathcal{S} \, \exists$ *a coalition structure* $\mathbf{c} \in \mathcal{S} \mid \mathbf{b} \ll \mathbf{c}$.

Similarly, the definition first indicates that any coalition structure **a** that belongs to the DFCS is farsightedly stable, or belongs to a cycle. Second, if a coalition structure **b** does not belong to the DFCS, it is not farsightedly stable. Furthermore, there exists another coalition structure $\mathbf{c} \in DLCS$, which dominates **b** indirectly.[8]

As the indirect domination includes the direct domination, $Coal_{fs} \subseteq Coal_{dd}$, this indicates that the DFCS is usually a subset of the DDSCS[9]; only rarely can they be identical.

3.2 | Multiple farsighted stable coalitions

In this section, we discuss the formation of multiple farsighted stable coalitions.

When multiple coalitions are formed, one has to consider two different kinds of interaction among coalitions, and between coalition and single players:

- one interaction happens between coalition and single players while number of coalition is fixed; in this case, one can talk again for indirect internal, external, and subcoalition domination
- one interaction occurs among coalitions as well as between coalitions and single players while coalition number can possibly change. We should check if this interaction results that coalition structure f_2 dominates the initial coalition structure f_1.
  During the inspection of player exchange among coalitions as well as between coalitions and single players, three essential (sub)interactions can happen:

  i. A coalition C of initial coalition structure a_1 can be dissolved, its members can join other coalitions or become single members and form another coalition structure a_2. It is clear that in the final coalition structure a_2, the members of coalition C receive higher profits compared to the profit in the initial coalition structure a_1 where coalition C takes part; this is a necessary condition that the coalition structure a_2 dominates the initial coalition structure a_1, as we consider only interactions that leads to direct or indirect domination (feasible interaction).

  ii. A coalition C can be formed that originates from initial coalition structure b_1, its members result from single players or coalitions which are actually formed. It is clear that in the final coalition structure b_2, the members of coalition C receive higher profits compared to the profit in the initial coalition structure b_1 where coalition C does not take part; this is a necessary condition that the coalition structure b_2 dominates the initial coalition structure b_1, as we consider only interactions that leads to direct or indirect domination.

  iii. Coalitions in our coalitions structure d_1 can exchange members and a new coalition structure d_2 is formed. Please note that no new coalition is formed and no coalition is dissolved.

First, we have to check if a coalition can be dissolved; if yes, a coalition C can be dissolved, then we have to find out if in the new coalition structure another coalition can be dissolved. We inspect all the ways that a coalition C can be dissolved. We stop when we find a coalition structure a_n, where no coalition can be dissolved that results in another coalition structure a_{n+1}, which dominates the coalition structure a_n.

There are many ways that one coalition C can be dissolved. Let assume that the initial coalition structure a_1 has $n+1$ coalitions, and coalition C has m members; all the ways N_{ds} that the coalition C can be dissolved are as in Equation (5) (here we assume that $m \geq n+1$, which is the most complicated case):

$$N_{ds} = Sub^{n+1}_{|C|}\frac{(n+1)!}{0!} + Sub^{n}_{|C|}\frac{(n+1)!}{1!} + \cdots + Sub^{2}_{|C|}\frac{(n+1)!}{(n-1)!} + Sub^{1}_{|C|}\frac{(n+1)!}{n!}, \tag{5}$$

where

- $Sub^{n+1}_{|C|}$, $Sub^{n}_{|C|}$ … $Sub^{1}_{|C|}$ are all the ways that the m members of coalition C can join n, $(n-1)$ … 1 coalitions and single players (or $(n+1), n$ … 1 subsets)
- $\frac{(n+1)!}{0!}$, $\frac{(n+1)!}{1!}$ ⋯ $\frac{(n+1)!}{n!}$ are the ways the $(n+1), n$ … 1 subsets can be permuted.

Second, we have to check if a coalition C can be formed. If a coalition C can be formed, then we have to find out if in the new coalition structure b_2 another coalition can be formed that results in another coalition structure b_3, which dominates the coalition structure b_2. We stop when we find a coalition structure b_n, where no coalition can be formed that results in another coalition structure b_{n+1}, which dominates the coalition structure b_n.

There are numerous ways that a coalition C can be formed. Assume we have l players all together, n coalitions $C_1, C_2 \ldots C_n$ with $n_1, n_2 \ldots n_n$ members and s single players, $n_1 + n_2 + \cdots + n_n + s = l$; all the ways N_{fr} that a coalition C can be formed are as in Equation (6):

$$N_{fr} = \sum_{i=1}^{l-2n} C^{i}_{l-2n} = 2^{(l-2n)}, \tag{6}$$

where

- C^{i}_{l-2n} is the number of coalitions (subsets) with i elements from $(l-2n)$ players (the number 2 is placed because a coalition must have at least two members)

Finally, we have to check if the exchange members among coalitions can lead to another coalitions structure d_2 which dominates our initial coalition structure d_1. We stop when the exchange members among coalitions cannot lead to coalition structure d_{n+1} which dominates our actual coalition structure d_n.

If there exists farsightedly coalition structures $a_2 = (C'_1, C'_2 \ldots C'_t, l_1)$ dominating the initial coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$ where $C_i \cap C'_i \neq \emptyset$, the algorithms presented in Osmani (2014) are able to find this (and then coalition structure a_2 has to be tested, if there is another coalition structure a_3, which dominates it). If there is no coalition structure which dominates our initial coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$, algorithm will give the answer that our initial coalition structure a_1 cannot be dominated, and consequently is farsightedly stable, or belongs to a cycle.

The algorithm is computationally very expensive, but it can be used for any arbitrary coalition structure. But similar to model of Zermelo (1913) for solving chess, we would like to stress that checking for an arbitrary farsightedly stable coalition structure is computationally expensive but finite.

4 | COMPUTATION RESULTS FOR A SINGLE FARSIGHTED STABLE COALITION

We use the *per -member partition function* (or simple profit function) of player i (or country i) taken from the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Tol, 1999a,b, 2001, 2002c) which is briefly described in Appendix A:

$$v(i) = B_i - C_i = \beta_i \sum_{j}^{n} R_j E_j - \alpha_i R_i^2 Y_i. \tag{7}$$

The benefit function B_i is approximated as

$$B_i = \beta_i \sum_{j}^{n} R_j E_j, \tag{8}$$

β is the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table 1 shows the parameters of Equations (7), (8), and (9) as estimated by the FUND *for the year 2005*.

Specifically, the abatement cost function C_i is represented as:

$$C_i = \alpha_i R_i^2 Y_i, \tag{9}$$

where C denotes the abatement cost, R the relative emission reduction, Y the gross domestic product, indexes i denote the regions and α is the cost parameter.

The second derivative of $dv(i)^2/dR_i^2 = -2\alpha_i < 0$ as $\alpha_i > 0$. It follows that the profit function of every country i is strictly concave, and as a consequence has a unique maximum. Hence, the noncooperative optimal emission reduction is found from the first-order optimal condition:

$$dv(i)/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i). \tag{10}$$

If a region i is in a coalition with a region j, the optimal emission reduction is given by

$$dv(i+j)/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i). \tag{11}$$

Thus, the price for entering a coalition is higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.

Note that our welfare functions are orthogonal. This indicates that the changes in a country's emissions do not affect the marginal benefits of other countries (that is, the independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries, but they cannot affect the benefits derived by the members of the coalition.

The superadditivity property is satisfied:

Definition 4.1. A game is superadditive if for any two coalitions, $C_1 \subset P_{16}$ and $C_2 \subset P_{16}$:
$V(C_1 \cup C_2) > V(C_1) + V(C_2) \quad C_1 \cap C_2 = \emptyset.$

The *superadditivity property* means that if C_1 and C_2 are disjoint coalitions (here C_1 and C_2 can be single players too), they should accomplish at least as much by joining forces as by remaining separate; where P_{16} is the set of all single coalitions that 16 players can form. However, the game *very frequently (but not always)* exhibits *positive spillovers*. The positive spillover property is usually satisfied except for some coalitions that include members such as members Japan and South Korea or Australia and New Zealand, which have negative marginal benefits (negative β's) from pollution abatement.

As we know, the per-member partition function allows us to compute the farsightedly stable coalitions. Finding all profitable coalitions needs a simple algorithm, although the computational efforts are not small. One finds all coalitions and checks if all their members have higher profits in comparison to the fully noncooperative structure.

The numerical results yield 15 profitable two-member coalitions. As there are many profitable coalitions, we have numbered them: for instance, $2-13, 2$ means that a coalition has two countries, and 13 means that it is 13th on the list of two-member profitable coalitions. The profitable two-member coalitions are:

$$\begin{array}{llllll}
(2-1) & (USA, CHI) & (2-2) & (USA, NAF) & (2-3) & (USA, SSA)\\
(2-4) & (CAN, SAS) & (2-5) & (ANZ, EEU) & (2-6) & (ANZ, CAM)\\
(2-7) & (ANZ, SAS) & (2-8) & (ANZ, SIS) & (2-9) & (EEU, CAM)\\
(2-10) & (EEU, SIS) & (2-11) & (FSU, LAM) & (2-12) & (CAM, SIS)\\
(2-13) & (CHI, NAF) & (2-14) & (CHI, SSA) & (2-15) & (NAF, SSA)
\end{array}$$

The profitable three-member coalitions are introduced below (the superscript "fs" denotes farsightedly stable):

$$\begin{array}{llll}
(3-1) & (USA, LAM, CHI) & (3-2) & (USA, SEA, CHI)\\
(3-3) & (USA, CHI, NAF)^{fs} & (3-4) & (USA, CHI, SSA)^{fs}\\
(3-5) & (USA, NAF, SSA) & (3-6) & (CAN, EEU, SAS)^{fs}\\
(3-7) & (CAN, FSU, LAM)^{fs} & (3-8) & (CAN, CAM, SAS)^{fs}\\
(3-9) & (CAN, CAM, SIS) & (3-10) & (CAN, SAS, SIS)^{fs}\\
(3-11) & (JPK, NAF, SSA) & (3-12) & (EEU, CAM, SAS)^{fs}\\
(3-13) & (EEU, CAM, SIS) & (3-14) & (EEU, SAS, SIS)^{fs}\\
(3-15) & (CAM, SAS, SIS)^{fs} & (3-16) & (CHI, NAF, SSA)^{fs}
\end{array}$$

The profitable four-member coalitions are:

$$\begin{array}{llll}
(4-1) & (USA, LAM, SEA, CHI) & (4-2) & (USA, LAM, SEA, SSA)\\
(4-3) & (USA, LAM, CHI, NAF)^{fs} & (4-4) & (USA, LAM, CHI, SSA)^{fs}\\
(4-5) & (USA, SEA, CHI, NAF)^{fs} & (4-6) & (USA, SEA, CHI, SSA)^{fs}\\
(4-7) & (USA, CHI, NAF, SSA)^{fs} & (4-8) & (CAN, EEU, CAM, SAS)^{fs}\\
(4-9) & (CAN, EEU, CAM, SIS) & (4-10) & (CAN, EEU, SAS, SIS)^{fs}\\
(4-11) & (CAN, CAM, SAS, SIS)^{fs} & (4-12) & (EEU, CAM, SAS, SIS)^{fs}\\
(4-13) & (LAM, SEA, CHI, NAF) & (4-14) & (LAM, SEA, CHI, SSA)\\
(4-15) & (SEA, CHI, NAF, SSA)^{fs} & &
\end{array}$$

The profitable five-member coalitions are presented below:

$$\begin{array}{llll}
(5-1) & (USA, LAM, SEA, CHI, NAF)^{fs} & (5-2) & (USA, LAM, SEA, CHI, SSA)^{fs}\\
(5-3) & (USA, LAM, SEA, NAF, SSA)^{fs} & (5-4) & (USA, LAM, CHI, NAF, SSA)^{fs}\\
(5-5) & (USA, SEA, CHI, NAF, SSA)^{fs} & (5-6) & (CAN, JPK, LAM, SAS, SSA)\\
(5-7) & (CAN, EEU, CAM, SAS, SIS)^{fs} & (5-8) & (LAM, SEA, CHI, NAF, SSA)^{fs}
\end{array}$$

There is only one six-member and only one seven-member profitable coalition:

$$\begin{array}{ll}
(6-1) & (USA, LAM, SEA, CHI, NAF, SSA)^{fs}\\
(7-1) & (CAN, JPK, EEU, CAM, LAM, NAF, SIS)
\end{array}$$

In total, there are 56 profitable coalitions. All profitable coalitions are internally farsightedly stable. By checking for external and subcoalition stability, we find that we have 28 farsightedly stable coalitions: 1 six-member coalition, 7 five-member coalitions, 10 four-member coalitions, and 10 three-member coalitions.

It is essential to note that the *asymmetry of countries* does not allow *large profitable coalitions*. When coalition members maximize their joint welfare, the optimization process requires further emissions reductions in those countries where it is cheaper to decrease emissions (where the marginal abatement cost is low) until profit maximization is reached and the marginal abatement costs of the coalition members are equal. As a result, those countries which initially have a low marginal abatement cost (if the difference in marginal abatement cost among coalition members is also large before coalition formation) *do probably not satisfy the profitability condition*. On the other hand, the benefits from pollution abatement vary for different countries. This implies that countries that benefit less from pollution abatement *do probably not satisfy the profitability condition*. It follows that farsighted stability is a function of the asymmetry of countries. Free-riding does not allow large myopically stable coalitions and the asymmetry of countries does not allow large farsightedly stable coalitions under *the assumption that transfers are not allowed*.

5 | MYOPIC STABILITY

A game Γ is defined, as in Section 2; as already explained, a coalition structure fully describes how many coalitions are formed, how many members they have, and also how many single players there are. The relation $\rightarrow_{C_1}$ introduces the actions that are available to coalition C_1; $a_1 \rightarrow_{C_1} a_2$ indicates that if a coalition structure a_1 is the status quo, coalition C_1 can make a_2 a new status quo. The relation $\rightarrow_{C_1}$ makes the main difference in relation to the first game-theoretic approach of Section 2. In the previous farsighted game, it was unrestricted, but at this point the relation $\rightarrow_{C_1}$ is very restricted, as it allows only one-step single-player movement. So only one single country can leave or join a coalition in a given coalition structure.

Definition 5.1. A coalition structure **a** with an S_p set of coalitions in **a** and an S_s set of all single players in **a**, is myopically stable if and only if:

- every coalition $C \in S_p$ is profitable
- internal myopic stability $\forall\, player\, i \in C, \forall\, C \in S_p \quad v(i)^*_{i \in C} > v(i)^*_{C \setminus \{i\}}$
- external myopic stability $\forall\, player\, j \in S_s, \forall\, C \in S_p$

$$v(j)^*_{C \setminus \{j\}} > v(j)^*_{j \in C} \text{ or } \exists i \in C \mid v(i)^*_{C \cup \{j\}} < v(i)^*_{j \notin C}$$

$v(i)^*$ $v(j)^*$ are per-member partition function values of the countries i and j.

We first demand that all myopically stable coalitions *are profitable*. The set of profitable coalitions is S_p, and the number of profitable coalitions is $|S_p|$.

A coalition structure **a** is internally myopically stable if for every coalition member who leaves any coalition of **a**, the payoff (or profit, welfare) is decreased. A player $i \in C_i$, where $C_i \in S_p$ has S_p different ways to leave coalition C_i; in $(S_p - 1)$ other coalitions, or as a single player. So there are necessary $|C_i| * |S_p|$ inspections in order to find whether a certain coalition C_i is internally myopically stable. As there are S_p profitable coalitions, there is a necessity for many inspections—see equation

(12)—in order to test whether a certain coalition structure **a** with S_p profitable coalitions and the S_s single players is internally stable:

$$number\ of\ inspections\ for\ checking\ myopic\ internal\ stability = \sum_{i=1:|S_p|} |C_i|) * |S_p|. \tag{12}$$

A coalition structure **a** is externally myopically stable if for every country that joins any coalition of **a**, it decreases his profit or if a previous member of the coalition (which he joined) decreases its profit.[10] There are $|N| - |C_i|$ different players that can join a certain coalition $C_i \in S_p$, where $|N|$ is the total number of players, and $|C_i|$ is the number of players in C_i. As a consequence, we have to test $|N| - |C_i|$ times if any player of coalition C_i, or the new player that joins it are decreasing their profits. As there are $|S_p|$ profitable coalitions, there is a necessity for as many inspections—see equation (13)—in order to test whether a coalition structure **a** with $|S_p|$ profitable coalitions is externally stable:

$$number\ of\ inspections\ for\ checking\ myopic\ external\ stability = |S_p||N| - \sum_{i=1:|S_p|} |C_i|, \tag{13}$$

where $|C_i|$ is the number of members in coalition C_i, and $|S_p|$ is the total number of profitable coalitions in coalition structure **a**.

It is evident that if a coalition structure has only one coalition, then one can speak of an internal or external myopically stable coalition. The myopic stability considers only single-player movements. Therefore, players are myopic as they can see only one movement ahead. A country that leaves the coalition assumes that the rest of coalition members remains in the coalition, as well as nonmembers of the coalition (the countries that do not belong to the coalition) remain nonmembers.

We present below a necessary condition on the existence of single myopically stable coalitions.

Observation 5.1. If there exist a chain of internally stable coalitions $C_1, C_2, C_3, \dots, C_m$ such that:

- C_{i+1} is obtained from C_i by adding one member to C_i where $i \in \{1, 2 \dots m, m+1\}$
- every C_{m+1}, which is obtained from C_m by adding one member, is not internally stable

then the coalition C_m is myopically stable.

Proof. Note that claiming that every C_{m+1} is not internally stable has a direct consequence, namely, that C_m is externally stable. As we have assumed that C_m is internally stable, then it results that C_m is myopically stable. This completes the proof. ■

5.1 | Finding single myopically stable coalitions

The computation results of single myopically stable coalitions are presented in this subsection.

The single myopically stable coalitions are myopically stable coalition structures that contain only one coalition. First, all profitable coalitions are obtained. Finding all profitable coalitions needs a simple algorithm, although the computational efforts are not small. One finds all coalitions and inspects whether all their members have higher profits in comparison to fully noncooperative structure. Then each coalition is tested if it is internally and externally myopically stable. Altogether, there are 11 myopically stable coalitions, which are presented below:

(*CAN, SAS*),	(*ANZ, EEU*),	(*ANZ, CAM*),
(*ANZ, SAS*),	(*ANZ, SIS*),	(*FSU, LAM*),
(*USA, CHI, NAF*),	(*JPK, NAF, SSA*),	(*CHI, NAF, SSA*),
(*CAN, JPK, LAM, SAS, SSA*),		
(*CAN, JPK, EEU, CAM, LAM, NAF, SIS*).		

6 | PREFERRED STABLE COALITIONS

Indirect domination indicates how far coalition members can "see and change" in order to reach a coalition, where the members of the final coalition obtain higher payoffs.[11] However, with the help of indirect domination, we cannot answer the following question:

Suppose that we have two different farsightedly stable coalitions, which have mutual members. The following question could be posed: *Which farsightedly (or myopically) stable coalition coalition is most likely to be formed from the full -noncooperative structure?* Clearly, the most common starting point is the full-noncooperative structure.

We should use another criterion, namely, the preference criterion, which is defined below, in order to further refine farsightedly stable coalitions.

The formal definition of *preferred coalition* is presented below.

Definition 6.1. A coalition C_m is preferred over C_n, $C_m \geq C_n$ if and only if:
for the majority of countries $i \in C_m \cap C_n$ $v_{C_m}(i)^* > v_{C_n}(i)^*$,
$v_{C_m}(i)^*$, $v_{C_n}(i)^*$ are per-member partition function values of the country i as a member C_m and C_n.

A coalition C_m is preferred over C_n if the majority of their mutual countries obtain higher profit in C_m.

The coalitions that are more easily formed will not only be farsightedly (or myopically) stable but also preferred coalitions. Therefore, *the preferred farsightedly (myopically) stable coalitions* have a higher probability of being formed.

6.1 | Multiple preferred stable coalitions

In this section, the discussion is extended to the question of multiple stable coalitions. Due to the computational complexity, we restrict ourself to two coalitions, namely:

$$(USA,\ LAM,\ SEA,\ CHI,\ NAF,\ SSA)^{fs}$$
$$(CAN,\ EEU,\ CAM,\ SAS,\ SIS)^{fs}$$

Note that the costs of the emission reduction of a region are independent of the abatement of other regions and the benefits are linear. Consequently, in case of multiple coalitions, the changes in the payoff for all regions, which are not members of two coalitions, are identical; considering these regions, only the first part of payoff equation (7) is changed, namely, $\beta_i \sum_j^n R_j E_j$, which is identical for each of them. It follows that our two coalitions are farsightedly stable if there is no indirect domination, which is caused *by switching members between two coalitions*. This has been numerically verified. Thus, we conclude that our two coalitions can coexist and are farsightedly stable.[12]

The second coalition alone increases the average abatement levels by 18% and the average profit by 3.4% compared to the fully noncooperative structure. So, there are 11 regions out of 16 (approximately two-thirds of the countries) that can cooperate, and they improve the abatement level by around four times and profit by around two times in comparison to the fully noncooperative structure. This is an interesting result, as well one of the few optimistic ones from noncooperative game theory. This result is a consequence of using a complex stability concept such as farsighted stability. However, grand coalitions can still perform far better than our two coalitions. The grand coalition can further enhance the total profit by more than two times and the total abatement level by almost four times in comparison to our two coalitions, and hence there is still much room for improvement that cannot be used due to the selfishness of our players (countries).

We reinforce the conclusion that the cooperation of certain countries like the USA or China (all countries of the first coalition) is crucial for a successful international environmental policy. This means that it is not only essential that a large number of countries signs an IEA, but also that certain key countries must do so. Surprisingly, the WEU is not a participant in any coalition, and this contradicts reality. This may be because we are not considering any *commitment to cooperate* in our noncooperative game theoretic approach[13].

The preferred myopically stable coalitions are:

(*USA, CHI, NAF*), (*ANZ, SAS*), and (*FSU, LAM*)

There are more multiple myopically stable coalitions than farsightedly stable ones, but myopically stable coalitions have fewer coalition members. The preferred myopically stable coalitions improve the environment and welfare in comparison to the fully noncooperative structure. However, the farsightedly stable coalitions generate better results in terms of welfare and abatement levels compared to the myopically stable coalitions. Only the farsightedly stable coalition (*USA, LAM, SEA, CHI, NAF, SSA*) improves the welfare and abatement by 20% and 79% in comparison to all *three preferred myopically stable coalitions* together.

7 | COMPARING MYOPIC AND FARSIGHTED STABILITY: A CONCEPTUAL DISCUSSION

This section discusses the differences between myopic and farsighted stability, and furthermore details a description of the way from *the single coalition myopically stable coalition* (*USA, CHI, NAF*) to *the single coalition farsightedly stable coalition* (*USA, LAM, SEA, CHI, NAF, SSA*).

The myopically stable coalitions can be divided into three groups. The coalitions of the first group are subcoalitions of the farsightedly stable coalition (*USA, LAM, SEA, CHI, NAF, SSA*):

(*USA, CHI, NAF*), (*CHI, NAF, SSA*)

The coalitions of the second group have members like ANZ and JPK, which rarely form profitable coalition:

(*CAN, JPK, LAM, SAS, SSA*)
(*CAN, JPK, EEU, CAM, LAM, NAF, SIS*)
(*ANZ, EEU*), (*ANZ, CAM*)
(*JPK, NAF, SSA*)

The myopic coalitions of the third group are small:

(*CAN, SAS*), (*ANZ, SAS*), (*ANZ, SIS*), (*FSU, LAM*).

We claim that the myopic stability is based on two myopic features. One is clear, as *it allows only a single movement* of a coalition member. The next feature is that *it demands that there is no free-riding*.

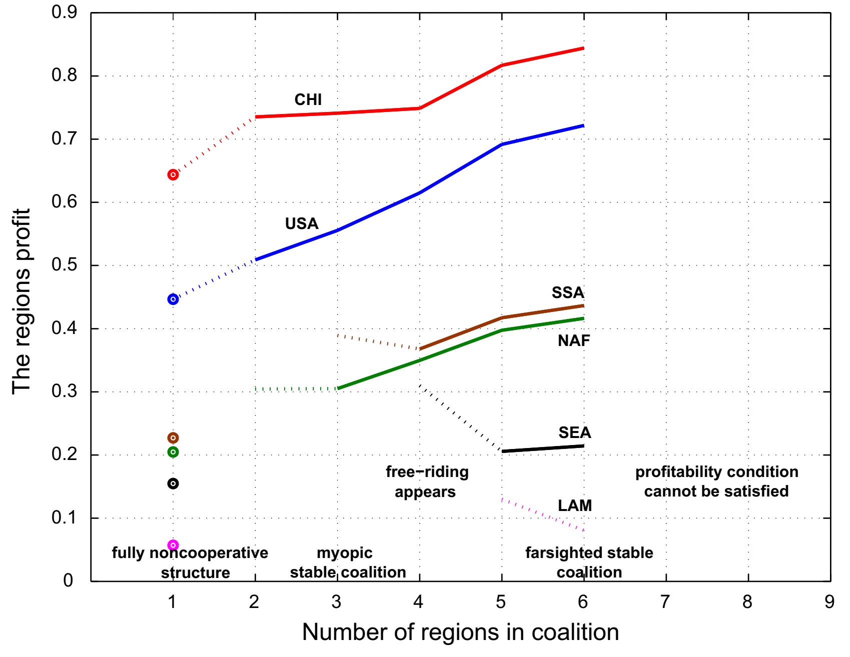

FIGURE 1 The comparison between the myopic and farsighted stability

If free-riding exists it means that the profits from the cooperation are also big. If there is no free-riding, this indicates that the profits from the cooperation are small. We take the coalition (*USA, CHI, NAF*) (or (*CHI, NAF, SSA*)) of the first group of the myopically stable coalitions. There is no free-riding initiative as the coalition is internally myopically stable. This signifies that if a country leaves the coalition, it decreases its profit. However, this implies that any subcoalition of two countries of our coalition does not reduce emissions as much as that a coalition member can take advantage of it and free-ride (the level of cooperation is low). Therefore, myopic coalition formation stops when free-riding appears. On the contrary, the farsightedly stable coalition formation does not stop when free-riding appears, but it stops when the profitability condition is not satisfied any further. Consequently, one can build the following scheme for describing a way from a myopic coalition to a farsightedly stable coalition:

$$(USA, CHI) \Rightarrow \underbrace{(USA,\ CHI,\ NAF)^{ds}}_{myopic\ stable\ coalition}$$

$$\Rightarrow \underbrace{(USA,\ CHI,\ NAF, SSA)}_{free-riding\ appears} \Rightarrow \cdots \Rightarrow \underbrace{(USA,\ LAM,\ SEA,\ CHI,\ NAF,\ SSA)^{fs}}_{profitability\ condition\ can\ not\ be\ satisfied\ further}$$

However, this is better seen in Figure 1. Along the *y*-axis we have single country profits in billions of dollars. Along the *x*-axis, there are some possible coalitions from a fully noncooperative structure to a myopically stable coalition (USA, CHI, NAF), and it ends with a farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$. When:

$x = 1$, we have $Atom_{structure}$ $x = 2$, we have (*USA, CHI*)
$x = 3$, we have (*USA, CHI, NAF*) $x = 4$, we have (*USA, CHI, NAF, SSA*)
$x = 5$, we have (*USA, CHI, NAF, SSA, SEA*) $x = 6$, we have (*USA, CHI, NAF, SSA, SEA, LAM*)

Every line represents the changes in profit of the respective country when different coalitions are formed. At the beginning of the dotted line, the respective country is not a member of a coalition. At the end of the dotted line, the respective country joins the coalition. Countries that join the coalition increase their profit until the myopically stable coalition (*USA, CHI, NAF*) is formed. After the coalition (*USA, CHI, NAF*) is formed, every country that joins it, decreases its profit. This indicates that the free-riding initiative exists, as these coalitions (all coalitions that contain the coalition (*USA, CHI, NAF*) as a subcoalition) are not internally myopically stable. After the farsightedly stable coalition (*USA, CHI, NAF, SSA, SEA, LAM*) is formed, the profitability condition is not satisfied any longer. This situation implies there is no larger farsightedly stable coalition as *farsighted stability is a function of profitability*, which is difficult to satisfy for a single large coalition. We have already clarified that the *asymmetry of countries* does not allow *large profitable coalitions*. This is a typical situation in a myopic coalition formation, and implies that myopically stable coalitions are frequently subsets of farsightedly stable coalitions. As single farsightedly stable coalitions are not very large (only around 40% of the countries), this implies that myopically stable coalitions are small (only around 20% of the countries). This occurs because *the internal myopic stability demands no free-riding, and no free-riding indicates that the cooperation brings only small improvements in both welfare and environmental quality* (this includes that the myopically stable coalitions are going to be small).

All the coalitions of second group cause a decrease in abatement level and a worsening of environmental quality in comparison to fully noncooperative structure. That is why they are grouped together. This takes place because they have as a coalition member *JPK* or *ANZ*, which can frequently (but not always) causes an abatement level decrease, as they have negative marginal damage costs of carbon dioxide emissions β (or a negative marginal benefit from emissions reduction), see Table 1. We focus on the coalition (*CAN, JPK, EEU, CAM, LAM, NAF, SIS*) (the discussion is similar to the other coalition of this group (*CAN, JPK, LAM, SAS, SSA*)), which belongs to the second group. Another distinctive feature of this coalition is that the cooperation is very "fragile," which means that if a country leaves the coalition then the coalition is not more profitable. This denotes that if a country leaves the coalition, then the coalition does not exist anymore and this stops the free-riding and even more. Besides, the above coalition increases the welfare very little. Then we claim that internal myopic stability causes big myopic coalitions (like (*CAN, JPK, EEU, CAM, LAM, NAF, SIS*) or (*CAN, JPK, LAM, SAS, SSA*)) that have very "fragile" cooperation and bring little improvement in welfare, or we have myopic coalitions that are small (like (*USA, CHI, NAF*) and are subcoalitions of a farsightedly stable coalition). Concerning myopic coalitions, we reinforce the conclusions of Barrett (1994) who uses only stylized cost-benefit functions and symmetric countries; we show that his conclusions hold in the case of more realistic cost-benefit functions and asymmetric countries too. One can see *the myopically stable coalitions as "minimum" (in welfare, environment improvement, and frequently in coalition size)*, *while the farsightedly stable coalition as "maximum"* that can be achieved by *game theory without transfers*. In real-world coalitions formation (such as Kyoto protocol *without transfers*), it is more reasonable to expect that the majority of the players (countries) are going to display less than a farsighted behavior but more than a myopic behavior. Consequently, we should predict the formation of coalitions that are bigger than myopically stable, but smaller than farsightedly stable coalitions.

The coalitions of the third group have in common that they are small, and they improve the welfare and environmental quality (in spite of that two of them have ANZ as a member, who has a negative marginal damage cost of carbon dioxide emissions β, see Table 1).

8 | CONCLUSIONS

This paper extends the analysis of Chwe (1994) on the issue of how to find farsightedly stable coalitions, and concentrates on the comparison between farsighted and myopic stability. The FUND model provides the cost-benefit functions of greenhouse gas emission abatement. The dynamic of the damage-cost functions of the FUND model controls the results.

The myopic stability concept assumes that the players are myopic and considers only single-player movements. The farsighted stability captures the farsightedness of the players. This implies that if a country considers deviating, it realizes that a deviation may trigger further deviations, which can worsen its initial position. All single farsightedly stable and myopically stable coalitions are found as well as their improvements to welfare and environmental quality. There are a lot more farsightedly stable coalitions than myopically stable coalitions, so farsighted stability increases room for cooperation.

We refine further the stable coalitions (farsightedly stable or myopically stable) to the preferred stable coalition. The preferred stable coalitions are more likely to be formed from a usual starting state such as a fully noncooperative structure in comparison to other stable coalitions.

We argue that myopic stability is myopic in two senses. First, because it considers only single-player movements. Second, because the internal myopic stability demands no free-riding. Nevertheless, no free-riding means that improvements (in welfare and environmental quality) from cooperation are small. Therefore, the internal myopic stability indirectly demands that the improvements from cooperation are small.

The size of the largest single farsightedly stable coalition and myopically stable coalition is small. The myopic stability argues that the free-riding makes it difficult to have large single stable coalitions. On the contrary, the farsighted stability argues that due to the asymmetry, the profitability condition is hard to satisfy for large single farsightedly stable coalitions. Moreover, the asymmetry of countries makes profitability condition hard to be realized and avoids maintaining big farsightedly stable coalitions. In spite of single myopic coalitions being small (only three countries) they bring improvements in comparison to fully noncooperative structure. However, farsightedly stable coalitions improve the welfare and environmental quality in comparison to myopically stable coalitions. We show that the myopically stable coalitions are often subcoalitions of farsightedly stable coalitions. Moreover, farsightedly stable coalitions can be frequently the largest stable coalitions that can be attained without side payments. Furthermore, they always produce the biggest improvements in environmental quality and welfare. In real-world coalitions formation (such as Kyoto protocol), it is more reasonable to expect that the majority of the players (countries) are going to display less than a farsighted behavior but more than a myopic behavior. Consequently, we should predict the formation of coalitions that are bigger than myopically stable but smaller than farsightedly stable coalitions. All those conclusions are valid *under the assumption that transfers are not allowed.*

Considering the multiple farsightedly stable coalitions leads to an optimistic result of game theory. Almost 70% of regions (40% in case of multiple myopically stable coalitions) can cooperate and improve significantly welfare and environmental quality. However, the multiple farsightedly stable coalitions clearly increase the welfare and abatement levels compared to the multiple myopically stable coalitions.

It will be interesting to consider more detailed regions and a game-theoretic approach which considers side payments.

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APPENDIX A: FUND MODEL

This paper uses Version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of the FUND corresponds to version 1.6, described and applied by Tol (1999a, b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reductions of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006).

Essentially, the FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, namely, the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In the FUND, the impacts of climate change are assumed to depend on the impact of the previous year, in this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be poorly represented in the first few decades of the model runs. The period 1950–1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes & Goldewijk, 1994). The period 1990–2000 is based on observations of the World Resources Databases (W.R.I., 2000). The climate scenarios for the period 2010–2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett, Pepper, & Swart, 1992). The 2000–2010 period is interpolated from the immediate past, and the period 2100–2300 is extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements, as well as the rate of the decarbonization of energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane, and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change.[14]

APPENDIX B: FINDING A MULTIPLE FARSIGHTEDLY STABLE COALITION STRUCTURE

If there exist farsightedly coalition structures $a_2 = (C_1', C_2' \ldots C_t', l_1)$ (with t coalitions, and l_1 single players), which dominate the initial coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$, where $C_i \cap C_i' \neq \emptyset$, the algorithm presented in Table B1 can find it (and then coalition structure a_2 has to be tested, if there is another coalition structure a_3, which dominates it). If there is no coalition structure, which dominates our initial coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$, the algorithm will give the answer that our initial coalition structure a_1 cannot be dominated, and consequently, is farsightedly stable or belongs to a cycle.

As already explained in Subsection 3.2 we check for the first and second interaction.

- One interaction happens between coalition and single players while number of coalition is fixed; in this case, one can talk again for indirect internal, external, and subcoalition domination.
- One interaction occurs among coalitions as well as between coalitions and single players while coalition number can possibly change (a coalition can form or dissolve). We should check if this interaction results that coalition structure f_2 dominates the initial coalition structure f_1. During the inspection of player exchange among coalitions as well as between coalitions and single players, three essential (sub)interactions can happen, which are lengthy explained in Subsection 3.2.

TABLE B1 Algorithm for finding farsightedly stable (EFS) coalition structures when t coalitions are formed, and l_1 players are single

Take the coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$ where l_1
is the number of single players, C_i $i \in \{1, 2, \ldots t\}$ are coalitions, and m is the total number of the players.
Calculate $\pi(1)..\pi(5)..\pi(m)$ the profits of this coalition structure.
Inspect the first interaction: for $i = 1 : t$
Inspect if coalition C_i is internally, externally, or subcoalitionally stable, or find the coalition C_{l_1} (where $C_{l_1} \cap C_i \neq \emptyset$).
Note at the moment exchanging members among coalitions is not allowed and the number of coalitions is fixed.
endif; end
Inspect the second interaction:
Inspect if the exchange of members among $C_1, C_2 \ldots C_t$, as well as the formation or dissolving of coalitions can find out
that the initial coalition structure $a_1 = (C_1, C_2 \ldots C_t, l_1)$
is indirectly dominated by the coalition structure $a_2 = (C_1', C_2' \ldots C_t', l_1)$
which has to be inspected for first and second interaction (and can possibly be farsightedly stable).
If by inspecting the first and second interaction, we are not able to find a coalition structure
which indirectly or directly dominates the coalition structure a_r (which is actually being tested)
the coalition structure a_r is farsightedly stable or belong to a cycle.
The coalition structure, which are indirectly dominated are excluded from
being a candidate of farsightedly stable coalitions.
END

It is crucial to mention that the algorithm is computationally expensive. However, similar to model of Zermelo (1913) for solving chess, we would like to stress that checking for an arbitrary farsightedly stable coalition structure is computationally expensive but possible, and finite.

ENDNOTES

[1] We consider only *economic incentives* that a region has to join a coalition for environmental protection. Other factors like commitment to cooperation are not taken into account.

[2] This paper is conceived as the second part of the paper Osmani and Tol (2009); given that, the intersections between them are inevitable.

[3] The algorithms how to find single farsightedly stable coalitions are introduced in Osmani and Tol (2009), so we are not repeating them here.

[4] Please note that subcoalition domination is always of indirect domination in nature; in any simple subcoalition domination there are always two steps; on the first step, some countries leave the coalition, and on the second one, some countries are join it. External (or internal) domination can be of a direct nature too; for example, two countries join the coalition (or leave it), and the coalition domination process ends.

[5] In Page and Wooders (2009), the authors raise the question of existence of the indirect dominant stable core. As in our case we have profitable coalitions, and per-member partition functions are concave, we do not need to worry about the existence of indirect dominant core.

[6] The algorithms of tables A.1 and A.2 in Osmani and Tol (2009) (see Appendix) fully describe the procedure of finding single farsightedly stable coalitions. As mentioned before we do not find it necessary to repeat them here. One of the reasons is to keep the length of the paper to a reasonable size.

[7] All computational programs in Matlab can be provided on request.

[8] We have independently reached a similar definition to Herings, Mauleon, and Vannetelbosch (2010). But Herings et al. (2010) also give existence proof of farsightedly stable sets, while we are concentrating on the question of how to find farsightedly stable coalitions.

[9] We also assume that in the case of direct domination players (which are not farsighted) do not free-ride. This is peculiar, but it can be justified because the free-riding is going to reduce the ability of players to find out if a coalition structure is directly dominated or not.

[10] In open membership games, the definition of myopic stability demands only that a country that joins a coalition reduces its profit (Barrett, 1994). It is more realistic (as an exclusive membership game in our case) to add the second part that a previous member of the coalition reduces his profit.

[11] The discussion in this section is more relevant for farsighted stability, but it can somehow be applied to myopic stability too. We simply grant members of myopically stable coalitions the possibility of choosing between different myopically stable coalitions (which is an *ad hoc* assumption).

[12] We introduce an observation that considers the division of farsightedly stable coalition in two or more coalitions.

Observation 6.1. A farsighted stable coalition cannot be divided in two or more coalitions.

Proof. Suppose that a coalition with six countries is divided into two subcoalitions with three countries (without loss of generality). Country members maximize their total profit in all coalitions. Suppose that maximum value found for the large coalition is $Prof_1$ and for two subcoalitions are $Prof_a$ and $Prof_b$ (it is clear that those maximum points are reached for different values of abatement levels R). Note that $Prof_1$ is a unique maximum because the Hessian matrix is negative definite, so we have a strict concave function. As a consequence $Prof_1 > Prof_a + Prof_b$, otherwise it contradicts the fact that $Prof_1$ is unique. This implies that at least one country has reduced profit (when the coalition is divided) so that the inducement process is not possible. Note that the proof is true also in case that many farsighted stable coalition coexist. ■

[13] On the contrary, in a cooperative approach WEU is a key player, but the cooperative attitude is beyond the scope of our paper. The WEU is always a member of coalitions (CHI, FSU, and USA too) that bring the maximum welfare improvement, although they are not stable.

[14] This is a short summary of the FUND; for a detailed description, please read more the FUND webpage: http://www.fund-model.org/home.